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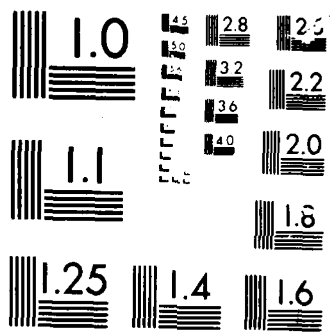
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# Magnetic Reconnection in a Non-Maxwellian Neutral Sheet

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The collisionless tearing-mode instability is believed to play an important role in magnetospheric reconnection processes. It has been found that the linear growth rate for a non-Maxwellian neutral sheet can be enhanced by a few orders of magnitude in comparison with the conventional isotropic case and that the short wavelength perturbations ($k\delta \gg 1$) are strongly favored, where $\delta$ is the characteristic half-width of the neutral sheet. For typical magnetotail parameters, it is found that the linear e-folding time can be reduced to a small fraction of a minute. The resulting small scale islands are expected to coalesce rapidly. The additional free-energy is the particle energy in the form of non-Maxwellian distribution. Differential equation analysis and full integro-differential analysis using exact unperturbed orbits are discussed. Physically, if non-Maxwellian features are generated in the plasma distribution by changes in external conditions such as the solar wind conditions, then the magnetotail may become strongly unstable, resulting in rapid development of small scale islands, coalescence and reconnection. This process may manifest itself as "triggering" of substorms following such changes.


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## CONTENTS

# MAGNETIC RECONNECTION IN A NON-MAXWELLIAN NEUTRAL SHEET

## I. Introduction

The collisionless tearing mode (Furth, 1962; Pfirsch, 1962; Laval et al, 1966) has attracted considerable attention in connection with the earth's magnetotail (Coppi et al, 1966; Schindler, 1966). It was suggested (Coppi et al, 1966) as a possible mechanism for magnetic field reconnection in the magnetosphere. The tearing mode may also be relevant to the dayside magnetopause (e.g., Greenly and Sonnerup, 1981; Quest and Coroniti, 1981). The basic idea is that the magnetic field energy stored in the magnetotail as a result of interaction with the solar wind is released in other forms of energy via reconnection processes. The collisionless tearing mode is a possible instability that allows necessary changes in the magnetic topology in the absence of resistivity.

The geometry most often used to model the magnetotail is the neutral sheet geometry. The standard analysis (e.g., Laval et al, 1966) uses a Maxwellian plasma distribution function. However, in a collisionless plasma such as the magnetotail, the motion of particles parallel to the magnetic field is decoupled from the perpendicular motion and non-Maxwellian features are likely to persist. Laval and Pellat (1968) showed that the collisionless tearing mode ($\underline{k} \parallel \underline{B}_0$) can be strongly modified by weak electron temperature anisotropy, $|T_{e\perp}/T_{e\parallel} - 1| < \rho_e/\delta \ll 1$, where $\underline{k}$ is the wave vector, $\underline{B}_0$, is the equilibrium magnetic field, $\rho_e$ is the typical electron Larmor radius, $\delta$ is the characteristic half-width of the neutral sheet, and $T_{e\perp}$ and $T_{e\parallel}$ are the electron temperatures associated with the particle motion perpendicular and parallel to $\underline{B}_0$, respectively. Subsequently, Forslund (1968) obtained an approximate dispersion relation with weakly anisotropic electrons. The work showed a substantial enhancement of the tearing-mode growth rate for $T_{e\perp} > T_{e\parallel}$, consistent with the result of Laval and Pellat (1968).

In the work of Forslund (1968), the effects of axis-crossing ion orbits extending beyond the electron inner region of the order of $(\rho_e\delta)^{1/2}$ were taken to be negligible (the conventional "two-region"

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approximation). Recently, Chen and Palmadesso (1984) have shown the existence of an ion intermediate region with a thickness of the order of $(\rho_i \delta)^{1/2} >> (\rho_e \delta)^{1/2}$ where the axis-crossing ion orbits make a major contribution. Inclusion of the ion intermediate region (the "three-region" approximation) shows that a given degree of ion anisotropy $(T_{i\perp}/T_{i\parallel} > 1)$ can increase the growth rate by nearly one order of magnitude over the result obtained using the two region approximation. Furthermore, in the two-region approximation, because the ion anisotropy effects are neglected, a neutral sheet with $(1 - T_{e\perp}/T_{e\parallel}) \approx \rho_e/\delta << 1$ is completely stable unless unrealistically high degrees of ion anisotropy is included. However, the three-region treatment shows that only modest ion anisotropy is needed to destabilize such a neutral sheet. This is of particular interest since any significant anisotropy in the electron population would tend to be isotropized on very fast time scales (see, for example, Coppi and Resenbluth, 1968). The time scale for the ions is longer, of the order of a minute, making it more relevant for magnetotail reconnection processes.

The three-region approximation also shows that a more adequate treatment of physically interesting systems containing anisotropic ions requires an accurate treatment of large ion orbits. In the above works, the complicated equilibrium orbits and orbit integrals were approximated. The inability to treat orbits exactly leads to a number of limitations such as the constant-$\psi$ approximation (i.e., $\psi$ is constant in the inner region) and weak anisotropy. In addition, if anisotropic ion effects dominate in the ion intermediate region while the electrons still dominate in the inner region, then the orbits for both species with disparate scale sizes must be treated accurately. Holdren (1970) carried out full integro-differential calculations of the tearing mode in a (relativistic) neutral sheet. In this work, the orbits were calculated numerically and an iterative method was used with discrete variables. As a result, the numerics required were substantial. Recently, Chen and Lee (1985) developed an integro-differential method which treats all the equilibrium orbits exactly and analytically for both species. This method makes it possible to remove the above limitations and they provided an accurate treatment of highly non-Maxwellian neutral sheet plasmas with minimal numerical calculation. Indeed, it was found that the eigenmode structure is highly localized at the null plane and that the constant-$\psi$ approximation is not valid for the non-Maxwellian case.

In this paper, we incorporate the recent results into a model of magnetic reconnection in the magnetotail. We will first review the theoretical results described above pertaining to the non-Maxwellian collisionless tearing-mode instability in a neutral sheet.

## II. The Non-Maxwellian Tearing Mode (NMTM)

Consider a neutral sheet whose magnetic field profile is given by $\underline{B}_0(z) = B_x(z)\,\hat{\underline{x}}$ such that $B_x(-z) = -B_x(z)$. The current density is given by $\underline{J}(z) = J_0(z)\hat{\underline{y}} = (c/4\pi)\underline{\nabla} \times \underline{B}_0$ with $J_0(-z) = J_0(z)$. The equations of motion admit three independent constants of motion; $H_\perp = (1/2)mv_\perp^2$, $P_y = mv_y + (q/c)A_y(z)$, and $H_\parallel = (1/2)\,m\,v_\parallel^2$ where $v_\perp^2 = v_y^2 + v_z^2$ and $v_\parallel = v_x$. Here $\underline{A}(z) = A_y(z)\,\hat{\underline{y}}$ is the equilibrium vector potential and the equilibrium electric field is set equal to zero. The tearing instability can be described by perturbations of the form $\hat{\psi}(x,z,t) = \psi(z)\exp(ikx - i\omega t)$ where the wavevector $\underline{k} = k\hat{\underline{x}}$ is parallel to the equilibrium magnetic field. Although not necessary, we will consider perturbations with $|\omega| < \omega_{ci}$ and neglect perturbed scalar potential. We assume charge neutrality to first order.

We consider a class of equilibria described by distribution functions of the type $F_j = F_j(H_\perp, P_y, H_\parallel)$ where j is the species index. Using the standard method of characteristics, the first order Vlasov distribution function for each species can be written as

$$f_j = \frac{q_j}{c}\frac{\partial F_j}{\partial P_{yj}}\psi + i\omega q_j \frac{\partial F_j}{\partial H_{\perp j}} S_j - ikq_j\left(\frac{\partial F_j}{\partial H_{\parallel j}} - \frac{\partial F_j}{\partial H_{\perp j}}\right)v_x S_j, \qquad (1)$$

where $\psi$ is the perturbed vector potential $\psi = A_y$ and $S_j$ is the orbit integral given by

$$S_y = -\frac{1}{c}\int_{-\infty}^{t} dt' v_y' \psi. \qquad (2)$$

The integration is carried out along equilibrium orbits. The perturbed vector potential then satisfies the equation

$$\frac{d^2\psi}{dz^2} - k^2\psi + \frac{4\pi}{c} J_{1y}(z) = 0 \qquad (3)$$

where

$$J_{1y} = \sum_j q_j \int d^3\underline{v}\, v_y f_j.$$

As a general remark, the full solution of the first-order problem can be obtained by solving the integro-differential equation (3). In the work of Forslund (1968), an approximate dispersion relation for weakly anisotropic electrons was obtained using (two) velocity moments to express the orbit integral. Essentially the same dispersion relation was obtained by Chen and Palmadesso (1985) by matching the inner $|z| \leq (2\rho_e\delta)^{1/2}$ and outer $(|z| > (2\rho_e\delta)^{1/2})$ solutions which are both analytically accessible. In this work, the straight-line orbit approximation (Coppi _et al._, 1966; Dobrowolny, 1968) was used for the axis-crossing orbits in the electron inner region for both species. Both approaches, however, neglect the fact that the axis-crossing ion orbits extend far beyond the electron region. By including the axis-crossing ion orbits, Chen and Palmadesso (1985) showed the existence of an ion intermediate region, $(2\rho_e\delta)^{1/2} < |z| < (2\rho_i\delta)^{1/2}$, in which the anisotropic ion contribution dominates. By matching the solutions in the three regions, they found that, for a given degree of anisotropy, the growth rate based on the three-region approximation can exceed, by nearly one order of magnitude, the growth rates obtained by the two-region approximation. Figure 1 summarizes these results, showing the growth rates for several values of $T_{i\perp}/T_{i\parallel}$ with isotropic electrons. In particular, Curve d ($T_{i\perp}/T_{i\parallel} = 1.15$) which is obtained using the three-region approximation is significantly higher than Curve e which is obtained by the two-region approximation for the same value of $T_{i\perp}/T_{i\parallel}$. Note that the maximum-$\gamma$ wavelengths are considerably shorter for $T_{i\perp}/T_{i\parallel} > 1$ than the isotropic case.

In the above works, various approximations were used to treat the orbit integrals such as the straight-line orbit approximation, constant-$\psi$ approximation and expansion in terms of velocity moments. These simplifications constitute severe limitations on the applicability of the analyses to physically interesting systems. Chen and Lee (1985) developed an integro-differential equation method which uses all the equilibrium orbits for both species exactly and analytically. They showed that the dispersion relation for $|\omega| < \omega_{ci}$ has the general form

$$\frac{\bar{\gamma}}{\bar{k}} = \left(\frac{\rho_e}{\delta}\right) D \tag{4}$$

where $\bar{\gamma} = \gamma/\omega_{ci}$ with $\omega_{ci} = eB_0/m_i c\ B_0$ and $\bar{k} = k\delta$. Here, D is a universal function of $T_{e\perp}/T_{e\parallel}$, $T_{i\perp}/T_{i\parallel}$ and $T_{e\perp}/T_{i\perp}$. Using the Galerkin method, they solved the integro-differential equation (3) and obtained the the universal function D and the eigenmode structure. Figure 2, reproduced from Chen and Lee (1985), shows the dispersion relation for several values of $T_{e\perp}/T_{e\parallel}$. The preferred wavelength is seen to be reduced significantly although the neglect of the scalar potential did not allow the accurate determination of the value of k for the maximum growth rates. In this work, both species are allowed to be highly non-Maxwellian. As a result, the instability is dominated by the electrons. A non-Maxwellian ion population with isotropic electrons has similar behavior but with smaller enhancement of the growth rate. A recent numerical simulation study (Ambrosiano et al, 1986) closely supports the behavior described above.

## III. Magnetic Reconnection in a Non-Maxwellian Plasma

Equation (1) shows that the type of non-Maxwellian features must be representable by distribution functions of the form $F = F(H_\perp, P_y, C)$, since the first two terms are the usual tearing terms. Here, C is a constant of motion independent of $H_\perp$ and $P_y$. In the above discussion, we have used the case with $C = H_\parallel$. Note that it is possible to construct a non-Maxwellian distribution of the form $F(H_\perp, P_y)$, etc. However, this type of distributions can only give rise to the conventional tearing mode. The

non-Maxwellian tearing mode, in effect, consists of two parts; the usual tearing mode and the part driven by the non-Maxwellian distribution of particle energy. The latter process is generally much stronger. This suggests that the NMTM can rearrange the internal particle energy as well as the magnetic energy on a fast time scale (possibly as high as $\gamma \sim \omega_{ci}$). The instability should lead to the formation of small scale islands. The islands then should coalesce rapidly (Finn and Kaw, 1977), which is a well documented process (see, for example, Pritchet and Wu, 1979; Brunel et al., 1982; Tajima and Sakai,1986). This scenario is also supported by the simulation results of Ambrosiano et al. (1986). In addition, these results show that the conversion of magnetic energy to kinetic energy takes place faster and more efficiently. We note that the above process may play a role in "forced reconnection" since the driving forces may preferrentially increase the perpendicular temperature. The magnitude of anisotropy and hence the growth rate depends on the strength of the forcing function.

We now consider a possible role the non-Maxwellian tearing mode may play in a physical system such as the magnetotail. Consider a Maxwellian equilibrium neutral sheet. Suppose the particle distribution function undergoes some large-scale changes due to changes in the external conditions. This leads to a rearrangement of particle energy. If the system admits 3 independent invariants of motion as described in the preceeding paragraphs, then the free-energy associated with the non-Maxwellian features can drive the NMTM. This occurs along with the usual tearing mode. For typical magnetotail parameters, the linear e-folding time can be reduced to a small fraction of a minute depending on the non-Maxwellian features (Chen and Palmadesso, 1984; Chen and Lee, 1985). Subsequently, small scale ($k\delta \gg 1$) islands are formed which then coalesce rapidly. The entire process may manifest itself as a triggering of reconnection following changes in physical conditions. It may also appear to be explosive (Galeev et al., 1978; Terasawa, 1981; Coroniti, 1985; Tajima and Sakai, 1986).

The above process implies that the coupling of the solar wind to the internal particle energy of the magnetotail is important. The non-Maxwellian distribution that can be generated by external changes depends on the strength of the changes and can drive the instability accordingly.

In the context of a substorm, the substorm may appear to be triggered or directly driven in response to some changes in the solar wind conditions with the NMTM providing a mechanism for the "solar wind control". The time delay is determined by the fast non-Maxwellian tearing time scales and the subsequent coalescence of islands. It is interesting to note that there has been considerable effort to classify substorms in two basic categories; storage-unloading of energy and direct-drive by the solar wind (Akasofu, 1981) The above mechanism contains attributes of both types. In this regard, the differential memory of particle distributions suggested by Chen and Palmadesso (1986) provides a natural means for the generation of necessary non-Maxwellian distributions.

Finally, it has been suggested (Galeev and Zeleyni, 1976; Lembege and Pellat, 1982) the magnetic field component normal to the equatorial plane can modify the tearing mode properties significantly if the electrons are magnetized, possibly stabilizing the ion tearing mode (Schindler, 1974). However, Coroniti (1980) has pointed out that pitch angle scattering of electrons can effectively demagnetize the electrons so that the tearing mode can still be unstable. Recently, Chen and Palmadesso (1985) have shown that the normal component renders the single-particle motion in a quasi-neutral sheet nonintegrable so that the electrons may be only partially magnetized. In addition, Goldstein and Schindler (1973) and Swift (1985) have suggested that the ionospheric influences may also contribute to the destabilization of the (conventional) tearing mode. Thus, there are strong indications that the non-Maxwellian tearing mode is important for magnetotail dynamics.

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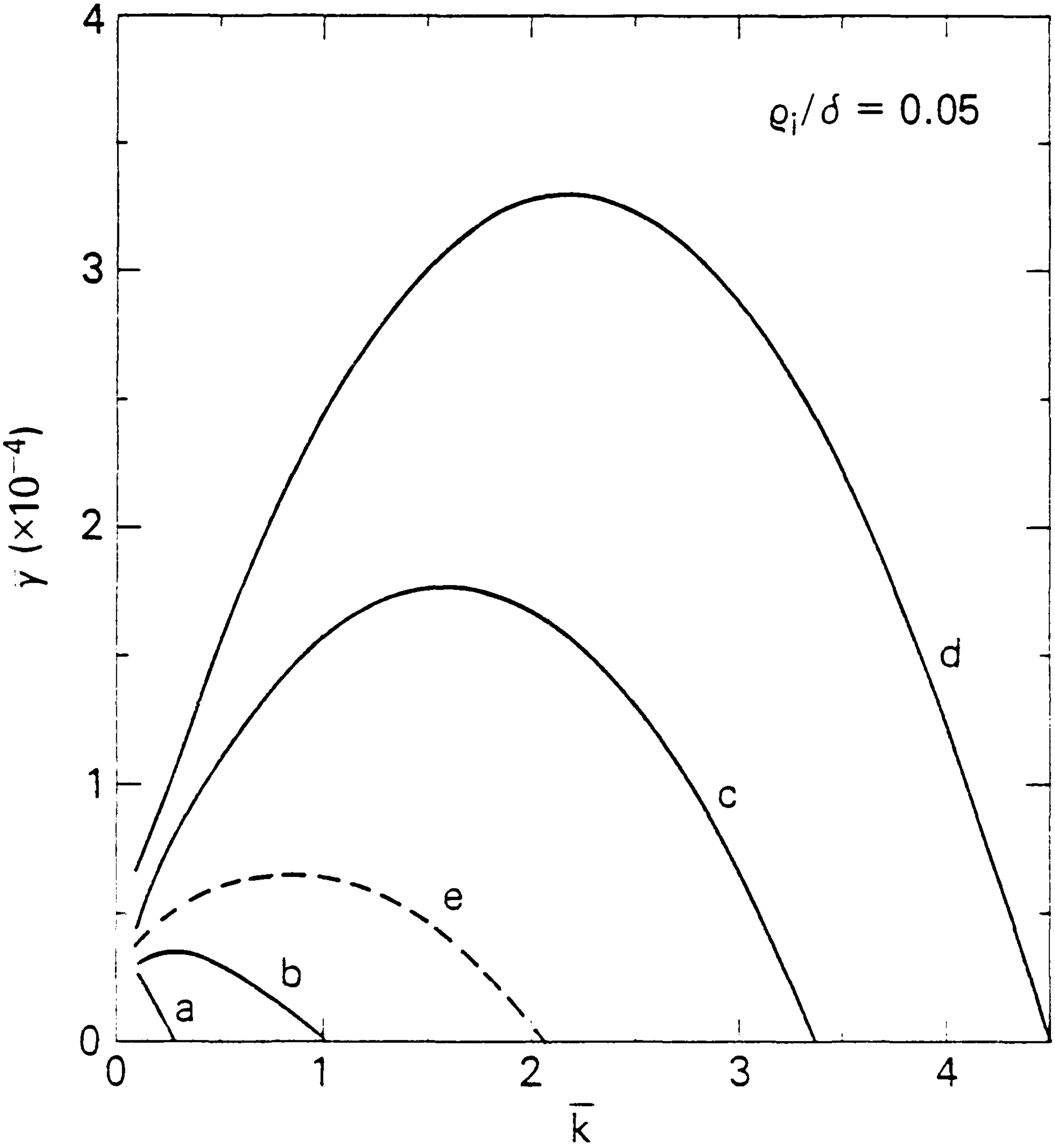


Fig. [illegible] Normalized growth rates $\bar{\gamma}$ using the three-region approximation. The values of $T_{i\perp}/T_{i\parallel}$ is (a) 0.9, (b) 1.0, (c) 1.[illegible], and (d) 1.[illegible]5. Curve e is the result of the two-region approximation for $T_{i\perp}/T_{i\parallel}$ = 1.[illegible]5.

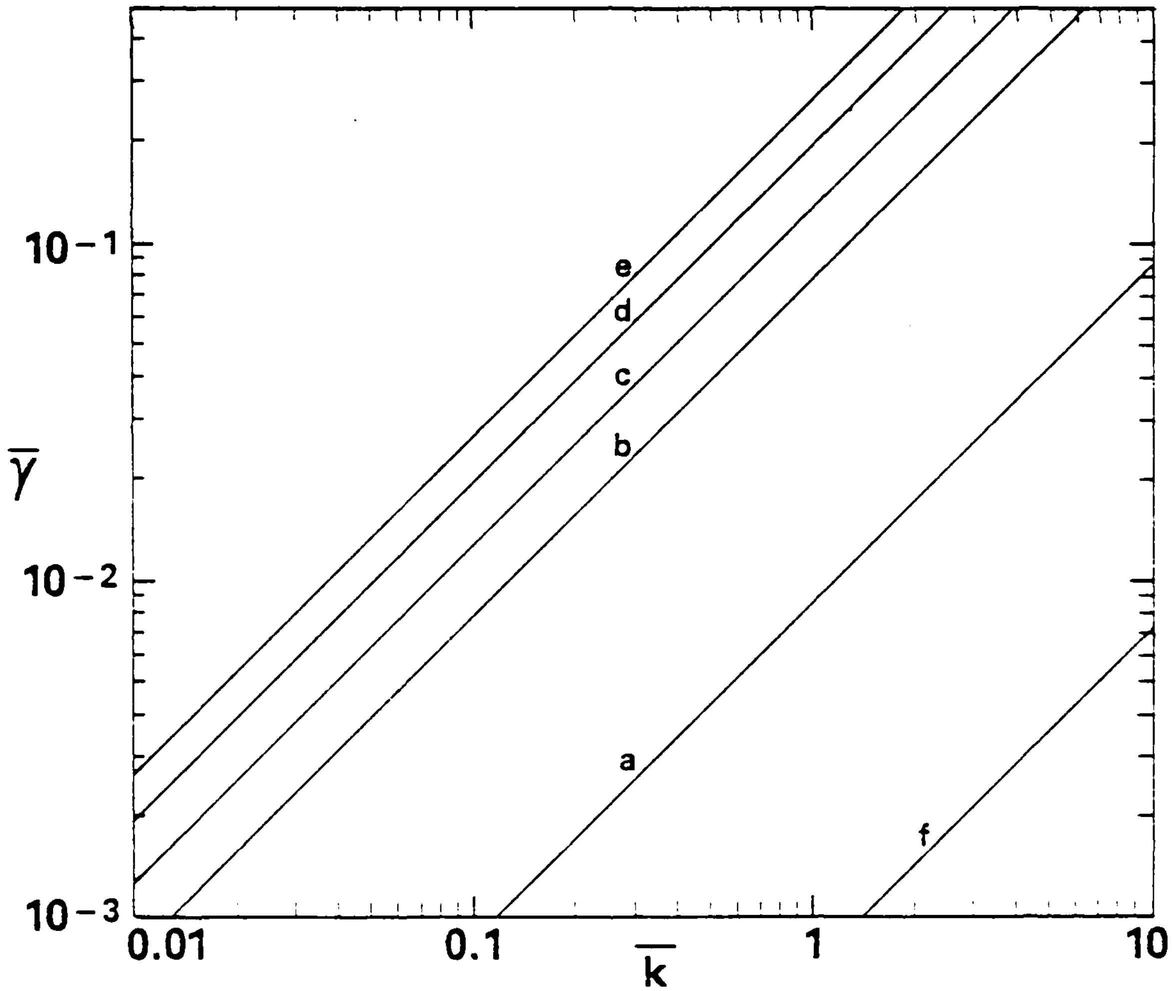


Fig. 2 (From Chen and Lee, 1985) The dispersion relation for a highly non-Maxwellian neutral sheet (equation (4)). The value of $T_{e\perp}/T_{e\parallel}$ is (a)1.0, (b)1.25, (c)1.5, (d)2.0, (e)3.0 and (f)3.0, the second branch to become unstable. Here, $T_{i\perp}/T_{i\parallel} = 1$, $T_{e\perp}/T_{i\perp} = 0.5$ and $\rho_i/\delta = 0.02$.

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